

**Nechako River White Sturgeon Recovery Planning:
Summary of Stock Assessment
and
Oct. 2-3, 2000 Workshop**

Final

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Executive Summary

The first informal meeting of the Nechako River White Sturgeon recovery group was held in Prince George, B.C. on Oct. 2-3, 2000. The objectives of the meeting were to: 1) review available data collected under the Fraser River White Sturgeon monitoring program to evaluate population trends in the Nechako River stock relative to Fraser River stocks; 2) review potential causes for a possible recruitment failure in the Nechako stock; and 3) discuss alternate experimental regimes and monitoring programs to resolve uncertainties for developing successful recovery strategies.

Prior to the workshop, we used standard stock assessment and modeling methods to address the issue of a recruitment failure in the Nechako sturgeon population. The analysis was reviewed and discussed at length at the workshop. A comparison of the age composition of the Nechako population with the other Fraser River stocks clearly showed an under-representation of younger fish in the Nechako population. A comparison of the age composition for the Nechako stock from data collected in 1982 with more recent data (1995-1999) provided a consistent picture of an ageing population with no significant recruitment for about the last 40 years. Finally, catch rates of young sturgeon from recent sampling have declined by at least 50% relative to rates from the 1982. While this final comparison is controversial owing to differences in sampling methodologies, the age composition data alone provide very strong evidence for recruitment failure.

We developed an age-structured population dynamics model to predict natural population age structure, track possible changes in stock size associated with apparent recruitment failure in recent decades, and predict population recovery rates should favorable conditions for recruitment be reestablished. This model uses standard methods for representation of recruitment, survival, and vulnerability to assessment sampling. As a dynamic model, it is "initialized" by estimating a natural or normal population structure, and changes over time are simulated by subjecting this structure to various hypotheses about past (beginning in 1950) and future recruitment rates.

The model accurately predicted age composition for the Nechako population collected in 1982 and 1995-1999 if a steep decline in the juvenile recruitment rate was initiated in the early 1960's. Good fits to the age composition data were also achieved if recruitment rate was varied according to a logistic relationship using the average June flow in the Nechako River at Vanderhoof. Estimates of the annual mortality rate and age-specific vulnerability from natural populations (i.e. Fraser River stocks) in conjunction with current age composition data for the Nechako population were used to reconstruct historical recruitment rates for Nechako sturgeon. The model predicted that there are currently about 150 mature females left in the Nechako population and that this number will decline to 25 by 2025. Immediate recovery of juvenile recruitment will not affect spawning population levels until after this date because of a minimum lag of 25 years between recruitment and maturity. The model forecasts underscore the urgency for initiating population recovery efforts as soon as possible.

A wide variety of potential hypotheses for causes of recruitment failure of the Nechako sturgeon population were discussed at the workshop. These ranged from effects directly related to flow diversion (discharge, temperature) to secondary effects

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(benthic habitat change, predation). Each hypothesis was evaluated based on how well historical trends in each factor compared to the model-based reconstruction of historical recruitment rates. Management actions that could reverse the effects of these factors were discussed. Research and monitoring requirements were also identified.

There was considerable uncertainty in identifying the key factor, or combination of factors, that caused the recruitment failure in the Nechako population, although the majority of factors were related to discharge. Most workshop participants supported the notion of an experimental management regime, where various factors would be purposely manipulated along with monitoring of key population parameters (spawning, juvenile catch rate, age composition). A number of potential experimental regimes were discussed, and the preferred option for most participants involved reshaping the existing release hydrograph to a more natural pattern exhibiting stronger seasonality.

Preface

The model and stock assessment presented in this document was developed by the authors prior to the Oct 2-3, 2000 recovery planning workshop. While the assessment and modeling methods and results were presented at the workshop, the interpretations and conclusions drawn from this work are those of the authors and do not represent a consensus across all workshop participants.

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1.0 Introduction

BC Fisheries initiated a variety of stock assessment activities on white sturgeon in the Fraser and Nechako Rivers beginning in 1995. The program provided evidence of potentially severe juvenile recruitment problem for the Nechako River stock. A recovery planning process was therefore initiated to develop mitigative measures and promote the recovery of this stock. As a first step in this process, a workshop was convened Oct. 2-3, 2000 in Prince George. The workshop focused on three questions:

1. What is the evidence supporting a decline in the recruitment of juvenile white sturgeon in the Nechako River?
2. What are the potential causes for this decline?
3. What experimental management regimes could be used to resolve uncertainties on the cause of recruitment problems to direct mitigation strategies?

Prior to initiating any recovery effort, a careful examination of the evidence for recruitment failure is required to firmly establish that a problem actually exists. We used standard stock assessment methods to analyze existing data in this regard. The workshop provided a good venue for key players in the recovery process to review the data and assumptions of our analysis.

The second question on causes for recruitment decline is critical towards identifying recovery strategies. A list of potential causes for the recruitment problem was developed. The plausibility for each cause was evaluated by comparing the historical timing of changes in that factor in relation to estimated patterns in historical recruitment rates from an age-structured population model. Management actions and research requirements associated with each recruitment failure hypothesis were discussed.

A successful recovery strategy for white sturgeon must address the causes for recruitment decline. As there was considerable uncertainty as to which factor, or combination of factors caused the Nechako sturgeon recruitment problem, the only rational option would be to develop a management program where various remediation strategies are evaluated in an experimental framework. Without any spatial controls, the experiment follows a Before-After design that consists of comparing responses of population indicators (e.g. frequency of spawning, age composition) from a treatment in one period with responses from a new treatment implemented in a later period. Some of details of this design, namely what treatments to apply, the duration and timing of the treatments, and the institutional challenges associated with implementing such an experiment were briefly discussed at the workshop and are reported here.

This document provides a summary of results used to evaluate historical trends in Nechako sturgeon recruitment and workshop discussions related to this analysis.

Section 2.0 reviews the data used to evaluate recruitment trends.

Section 3.0 reviews the mechanics and assumptions of the sturgeon population model used to make additional interpretations of recruitment trends. Predicted estimates of recruitment patterns over time are presented and evaluated based on current age structure data.

Section 4.0 summarizes the workshop discussions focused on identifying potential causes for the recruitment failure.

Section 5.0 summarizes discussions associated with the design of an experimental management program focused on identifying successful strategies for recovering the Nechako River white sturgeon stock.

2.0 Evidence for Recruitment Failure in the Nechako River White Sturgeon Population

We have examined considerable data that support the hypothesis that the juvenile recruitment rate for Nechako River white sturgeon is very low and not sufficient to support the current population. Recruitment failure is supported based on an evaluation of: 1) differences in the age composition between the Nechako and Fraser River stocks; 2) shifts in the age composition for the Nechako stock over time; and 3) differences in catch rates of Nechako juvenile fish over time.

To properly interpret age composition data, it is important to recognize that such data contain information about mortality, recruitment, and age-specific vulnerability (Fig. 1). If the population size is assumed to be stable over time, the slope of the age composition frequency distribution reflects the mortality rate from one age to the next. The steeper the slope, the greater the mortality rate (Fig. 1, top). Differences in age composition between two populations may also result from trends in recruitment rates (Fig. 1, middle). An expanding population, where the rate of recruitment is greater than what is required to maintain current population levels, will have an overrepresentation of younger fish, which appears as a steeper slope in the age composition frequency curve. A declining population will have an under-representation of young fish, which reduces the slope of the age composition curve. The shape of age frequency curve may also reflect differences in the vulnerability of different age fish to the sampling gear (Fig. 1, bottom). If young fish are underrepresented in the sampling, the age composition curve will have a right-skewed dome-shaped appearance.

2.1 Comparison of Nechako Stock Age Composition with Fraser River Stocks

The strongest evidence of juvenile recruitment problems in the Nechako River stock comes from a comparison of its age composition data with data from other Fraser River sturgeon populations (Fig. 2) based on sampling between 1995 and 1999 (RL&L 2000). The absence of younger fish in the Nechako stock is very apparent; very few fish less than 25 years old were caught and the modal age was 35-40 yrs. The under-representation of fish less than 5 years old seen in all populations is the result of low sampling efficiency for young fish.

The lack of young fish in the Nechako samples compared to every other Fraser population can be interpreted in two ways: (1) the Nechako stock has suffered severe recruitment failure for about 25 yrs.; or (2) Nechako juveniles are not vulnerable to sampling for some reason (behaviour, residence in habitats like lakes or the lower river where sampling would not detect them, undersampling of environments like the Stuart River, etc.). We consider the second of these interpretations as very unlikely, especially considering the wide variety of habitat conditions over which the sampling has successfully captured juveniles downstream from the Nechako. However, an important point needs to be made about this interpretation. There is no scientific way with available data to categorically reject the proposition that juvenile Nechako sturgeon are out there somewhere but just have not been sampled. This is an "existence argument" that

cannot be disproved, no matter how hard biologists work to find fish in unusual places with unusual methods. It can always be claimed that the fish are just around the corner, in some "black hole" that biologists have not yet discovered. It may be worth investing some effort to determine whether Nechako juveniles have some special headwaters life history strategy such as lake rearing in the Stuart system or downriver rearing. But the burden of proof for the black hole hypothesis is clearly on those who would claim that somehow Nechako sturgeon are different from sturgeon everywhere else in the Fraser basin.

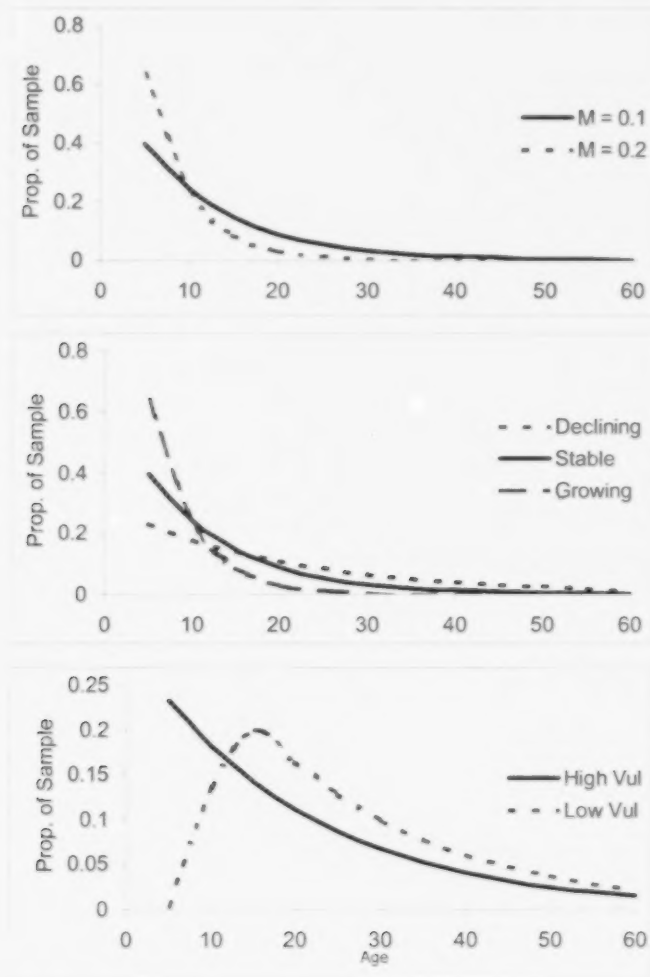


Figure 1. Effects of mortality rate (top), recruitment rate (middle) and age-specific vulnerability to sampling gear (bottom) on age composition data.

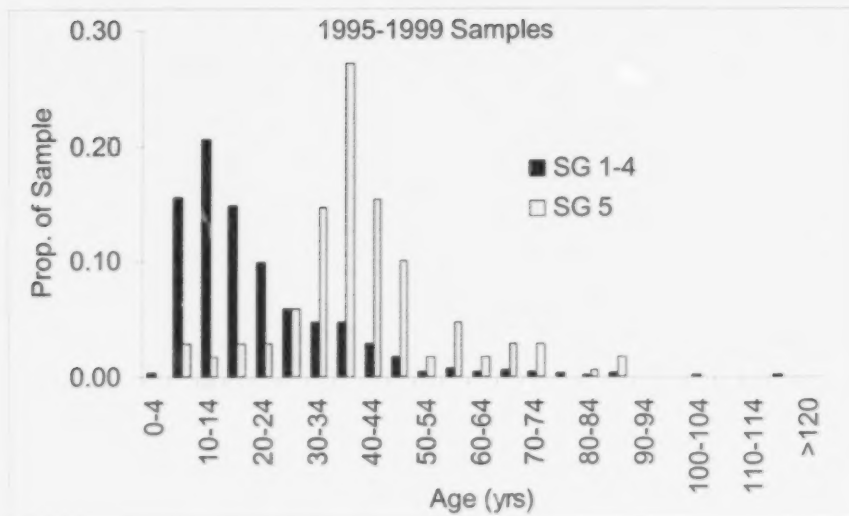


Figure 2. Comparison of age composition for the aggregate of Fraser River stocks (SG1-4) and the Nechako River stock (SG5).

During the October workshop, it was argued that if fish from the Nechako and Stuart Rivers are from the same stock, our conclusions about recruitment failure could be incorrect. This argument is wrong; recruitment failure applies to whatever stock of fish uses the Nechako River whether or not those fish spend some of the time in the Stuart system. That is, if some fish reproduce in the Stuart River, there are not enough of these young fish to offset the recruitment failure in the Nechako River.

2.2 Historical Changes in Nechako Stock Age Composition

A comparison of age composition of Nechako River sturgeon from samples taken in 1982 (Dixon 1986) with more recent data from the 1995-1999 sampling effort (RL& L 2000) clearly shows a shift in age structure that is consistent with the hypothesis of an almost complete recruitment failure occurring at least 25 yrs ago (Fig. 3). The most common age in the 1982 sample was 15-20 yrs compared to 35-40 yrs for the 1995-1999 samples. Note how the dominant age from the 1982 sampling shows up at about the correct age in samples taken 25 years later. If there had been significant juvenile recruitment between these dates, the modal age in the 1995-1999 sampling would have been much lower. Differences in sampling protocols (gear, times of deployment, sampling location) between 1982 and 1995-1999 as reviewed by Triton (2000) could have resulted in age composition differences between these two sampling periods. We see no pattern in these differences that would produce such a large shift in modal age of fish sampled. It would also be a really remarkable coincidence for the sampling bias to have shifted the modal age by exactly 25 years, just the interval between the two

sampling periods. We therefore conclude that differences in age composition between the 1982 and 1995-99 samples is evidence of recruitment failure in the Nechako River stock and not due to changes in sampling methodology.

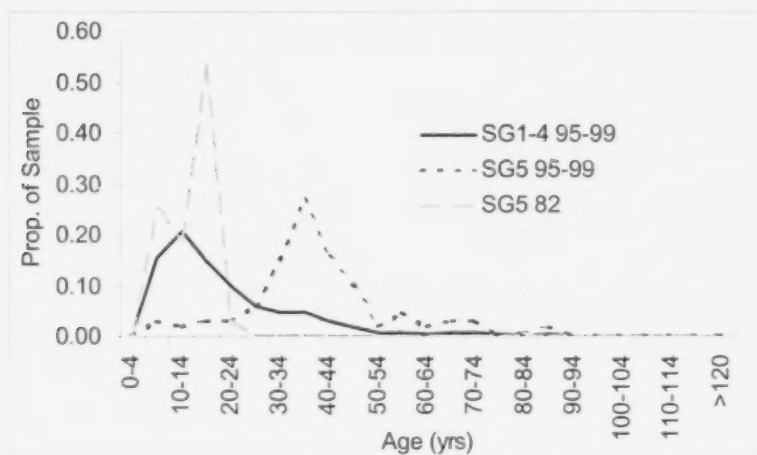


Figure 3. Comparison of age composition for the aggregate of Fraser River stocks (SG1-4) and the Nechako stock (SG5) based on data collected between 1995 and 1999, and 1982.

2.3 Interpretations of Decline in Catch Rates from 1982 to 1999

August catch per effort sampling in the Nechako River declined by roughly half from 1982-99 (Triton 2000), despite concentration of netting in the most productive times (night). The decline is even more severe if June-July sampling results for 1999 are included in the calculation of average catch per effort (an unnecessary and dangerous procedure, considering how common it is for catchabilities of fish to show strong seasonal change in fisheries sampling programs). Discussions at the workshop revealed considerable controversy over the interpretation of changes in catch per effort between the 1982 and 1999 sampling periods. The 1982 sampling protocol could not be replicated in 1999 due to sampling restrictions imposed by fisheries management agencies. Thus, changes in CPE between the two periods could be driven by changes in sampling protocols. However, the decline in CPE is consistent with other very strong evidence from age composition data supporting a decline in juvenile recruitment. In addition, the population dynamics model described below predicts a decline of similar magnitude from the early 80s to the late 90s, if we assume that there was severe recruitment failure beginning sometime between the early 1950s (initial Nechako dewatering) and 1970 when full water withdrawals to Kemano were established (see Fig. 6b).

3.0 Model Description

We developed an age-structured population dynamics model to predict natural population age structure, track possible changes in stock size associated with apparent recruitment failure in recent decades, and predict population recovery rates should favourable conditions for recruitment be reestablished. This model uses standard methods for representation of recruitment, survival, and vulnerability to assessment sampling (Hilborn and Walters 1992). As a dynamic model, it is "initialized" by estimating a natural or normal population structure, and changes over time are simulated by subjecting this structure to various hypotheses about past (beginning in 1950) and future recruitment rates. The natural population predicted age structure is compared to data from other Fraser River sturgeon stocks in order to estimate age vulnerability and annual survival rates, on the assumption that juvenile sturgeon from the Nechako are just as vulnerable to sampling as are juveniles for the other Fraser River populations (paucity of juveniles in recent samples due to recruitment failure, not a localized pattern of differentially low vulnerability to sampling).

The Fraser River White Sturgeon populations have been segregated by RL&L (2000) into the following five groups:

- SG1= Lower Fraser upstream to Hope;
- SG2 = Fraser River from Hope to Hells Canyon;
- SG3 = Fraser River from Hells Canyon to Prince George;
- SG4 = Fraser River upstream of Prince George;
- SG5 = Nechako River

Our assessment and modeling used data for the SG1-4 stocks as a 'control' or natural-system analogue to compare against the Nechako River stock.

3.1 Assessment of Natural Population Structure

We assume that age 1+ annual survival rates S_a (a =age, $S_a=e^{-M_a}$ where M_a =instantaneous mortality rate) are stable over time. Then a natural population will on average have a number N_a of age 'a' animals equal to R_0L_a , where L_a is survivorship to age 'a' defined recursively by $L_1=1$, $L_a=S_{a-1}L_{a-1}$ for $a>1$ and R_0 is average natural recruitment rate of 1 yr old sturgeon. If the relative vulnerability of age 'a' animals to sampling is v_a , the average natural vulnerable population size N_0 is then given by $N_0=R_0\phi_v$, where ϕ_v is the vulnerability "incidence function"

$$\phi_v = \sum_a L_a v_a. \quad (1)$$

This incidence function simply sums the expected number of survivors at age per age 1 recruit, times the relative vulnerabilities at age of these survivors. Note that for the natural population situation, the expected proportion $P^{(0)}_a$ of age 'a' fish in an age composition sample is given by

$$P^{(0)}_a = L_a v_a / \phi_v. \quad (2)$$

We can estimate some features (parameters) of the L_a and v_a patterns by varying these parameters so as to make $P^{(o)}_a$ correspond as closely as possible with observed $P^{(obs)}_a$ values.

Lacking enough data for more detailed analysis, we treat the survival rates for age 5+ fish (the only ones occurring in significant numbers in the samples) as independent of age, so $S_a = e^{-M}$ where M is a single instantaneous natural mortality parameter. The best evidence for the assumption of a constant survival rate is that similar patterns of decline in relative abundance with age occur in a wide range of sturgeon stocks from the Fraser Basin (RL&L 2000) and from the Columbia River as well (Beamesdorfer et al. 1995). For this species, age composition data cannot be used to infer possible age-dependence for survival rate since any such variation is confounded by selectivity to sampling over the ages 5 to 15 yrs.

We assume the vulnerabilities at age can be represented as a sigmoid, saturating function of age, and we use the function

$$v_a = a^s / (a_h^s + a^s) \quad (3)$$

to represent this assumption. Here, a_h is the age at which the fish are half as vulnerable as older (fully vulnerable) fish, and s is a "steepness" parameter for the function (higher values of s imply closer to a "knife edge" change in vulnerability near age a_h).

The age-independent mortality/sigmoid vulnerability assumptions give a remarkably close fit to aggregated age composition data for the lower river stocks (SG1-4) for 1995-99 (Fig. 4). The a_h parameter of eq. (3) is precisely estimated (at around 8 yrs), s is relatively well estimated (values in the range $s=5-10$ give similar fits), and M is very precisely estimated at 0.10. A good indication of uncertainty in these estimates can be obtained by comparing the estimates for individual stock groups (Table 1); the estimate of total mortality rate is quite stable, but estimates of the vulnerability parameters are much less precise. Note that a_h for the Nechako stock from recent samples (1995-99) is much greater than for other stocks and even for the Nechako stock sampled in 1982. This could be interpreted as a reduction in vulnerability-at-age during the 1995-99 sampling period. However, considering the same sampling methodologies were used for other stocks during this time, the larger a_h value more likely represents the absence of younger fish in the Nechako population.

Table 1. Estimates of vulnerability and mortality rate parameters for Fraser River sturgeon stocks based on sampling from 1995-1999. Estimates are least squares (sum of squared differences between observed and predicted age proportions by 5-yr age category).

Stock	Number of fish aged	age 50% vulnerability (a_h)	Vul. Power (s)	Mort rate M
SG1	282	17.00	2.90	0.13
SG2	195	7.66	4.38	0.10
SG3	381	7.87	5.25	0.15
SG4	48	5.40	12.64	0.06
Combined SG1-SG4	906	7.76	4.78	0.10
Nechako 1982 sample	57	12.05	3.24	0.09
Nechako 1995-1999 sample	200	35.5	10.5	0.12

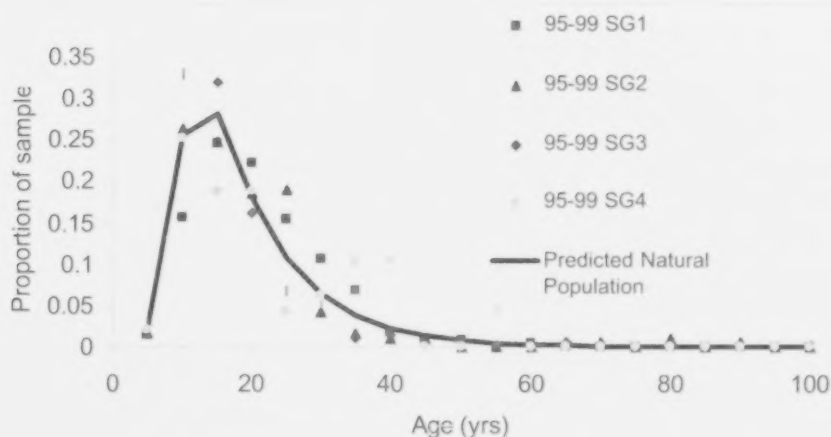


Figure 4. Comparison of age composition from the best-fit balanced sturgeon population (Predicted Natural Population) for the Fraser River aggregate stock and the observed age compositions from individual Fraser River stocks (SG1 - SG4).

The estimated value for M is cause for considerable concern. Over a very wide range of fish species, the empirical relationship reported by Pauly (1980) between M and the vonBertalanffy growth parameters L_{∞} , K has proven over the years to be a quite precise predictor of M ($M=1.7K$). For the vonBertalanffy parameter values reported for the various Fraser River sturgeon stocks, the Pauly equation predicts M to be in the range 0.03-0.05, with very little chance that M is as high as 0.1. Indeed, an M this high would virtually preclude some observations about Fraser sturgeon, such as very large fish with ages exceeding 200 yrs., unless mortality rate drops off very sharply for older, extremely rare fish. Other possible explanations for the apparent high M in the Fraser data are:

- (1) The lower river stocks are actually growing (with recruitments increasing at an average rate of around 6%/yr.), recovering from impacts of historical fishing near the turn of this century (fish older than 60 yrs may be scarce in the samples due to poor recruitments following the peak of the historical fishery);
- (2) Larger, older fish are less vulnerable to the sampling, due perhaps to being smarter or less active than mid-age fish, or to higher probability of residing in non-river habitats (large lakes, ocean) not included in the sampling.
- (3) There is severe bias in ageing procedures such that older fish are reported as being much younger than they actually are. This could result if older fish stop producing annuli.

If the M for immature and early mature age fish is indeed as high as 0.1, then the natural populations have considerably higher turnover (recruitment) rates than has previously been assumed, and should be correspondingly more "resilient" to disturbances (i.e. capable of faster recovery following successful mitigation). However, interpretations about historical stock trend based on lack of young fish in the Nechako stock are not strongly affected by assumptions about M (we would draw the same conclusions about changes in recruitment rates whether we analyze the age composition data using $M=0.03$ or $M=0.1$ for older fish). Using relatively high values of M has a potentially important implication for stock rebuilding rates. Since higher values of M imply higher recruitment rates, overestimates of M lead to overestimation of population recovery rates in modeled scenarios where recovery in recruitment is simulated.

Age composition analysis for Fraser sturgeon by Semakula and Larkin (1968) also indicated quite a high apparent total mortality rate (>0.1). DeVore et al. (1995) estimated M for Lower Columbia white sturgeon to be 0.1. Beamesdorfer et al. (1995) reported high total mortality rates for Columbia reservoir populations, and their apparent total mortality rates in conjunction with their direct estimates of exploitation rate would also suggest M around 0.1, at least for younger (<25 yr) fish. Semakula and Larkin mentioned that presence of very large, old fish in the Fraser (but not in their samples) might indicate M as low as 0.05; in his synthesis of M estimates, Pauly (1980) apparently included this low value in his statistical analyses despite lack of support for the value in the original Semakula and Larkin paper. What we suspect is happening is that M decreases greatly for very old fish (>60 -70 yrs) that are growing very slowly, so a few of them persist (and are highly visible) to extreme ages possibly without making much contribution to recruitment or overall population dynamics. However, it is also possible that older fish have been much less vulnerable to sampling in all the past studies, and are in fact present in considerable numbers.

3.2 Simulation of Historical and Future Population Trends

If natural mortality rates, growth, and size-age fecundity schedules are assumed stable, the most critical assumptions for population dynamics predictions are about recruitment rates. Following wide experience with fish population dynamics data (Myers et al. 1999 have examined recruitment patterns for over 600 fish populations worldwide), we elected to assume a Beverton-Holt relationship between annual egg deposition and age 1 recruitment, with the relationship modified over time by alternative hypotheses about changes in survival rate associated with various changes in habitat in the Nechako

River. That is, we assume that the number of age 1 recruits $N_{1,t}$ in any year t was/will be well predicted by the equation

$$N_{1,t} = H_t a E_t / (1 + b E_t) \quad (4)$$

where a and b are natural survival rate and habitat capacity parameters, H_t is a year-specific survival factor ($H=1$ for natural conditions), and E_t is total egg deposition in year t . E_t is calculated by summing numbers at age times estimated relative fecundities f_a at age:

$$E_t = \sum_a f_a N_{a,t} \quad (5)$$

Absolute scaling for fecundity is not necessary as these 'scale factors' are "absorbed" in the estimation of the recruitment parameters (a , b) as described below. Relative fecundities f_a are assumed proportional to body weight at age W_a , above a female weight at maturity W_{160} , where W_{160} is the female body weight for a female of length 160cm: $f_a = (W_a - W_{160})$ for $W_a > 160$, $f_a = 0$ for smaller fish.

The recruitment a , b parameters are estimated by first calculating a natural recruitment rate $N_{1,0} = R_0$ and egg deposition E_0 , then using relationships estimated by Myers et al between a and R_0/E_0 (a relative survival measure). By assuming a natural population size, $N_0 = 5000$, we calculate the egg deposition generated from this population given our maturity and fecundity schedule (E_0). While predictions about relative population decline are independent of the value used for N_0 , we elected to use $N_0 = 5000$ because that value, following recruitment failure, results in the current population size of 500 fish measured in the 1995-1999 mark recapture study (RL&L 2000). The age 1 recruitment ($N_{1,0}$) required to sustain this population level is computed based on the assumed survivorship. Myers has shown that the Beverton-Holt productivity parameter 'a' is generally a small multiple K , where $K=3-10$, of R_0/E_0 (the natural population recruitment rate per egg); we assume 'a' = $K R_0/E_0$ with $K=5$ as a conservative hypothesis for sensitivity of recruitment to parental egg deposition. So that the model will predict the base natural recruitment R_0 when $E_t = E_0$, we then set the habitat capacity scaling parameter $b = (K-1)/E_0$. Under this convention for parameterizing the recruitment model, the natural vulnerable population size N_0 becomes a "leading" parameter for simulations. That is, for any hypothesized N_0 , the natural population, in order to be stable, must have an annual recruitment rate equal to mortality loss $(1 - e^{-M})^* N_0$. N_0 and ϕ_v imply R_0 ($R_0 = N_0/\phi_v$), and R_0 along with the survivorships L_a implies E_0 . The K parameter mainly affects predictions of population recovery rate, with low K values implying insufficient adults left in 1999 to fully seed the juvenile rearing habitat and a recruitment decline about 30 years from now when recent low recruitments result in declines in the number of mature females.

Quite a good fit to 1990's age composition data is obtained if we simulate forward from 1950 while assuming that the recruitment-habitat multipliers H_t (relative reproductive success) declined linearly from 1.0 to 0.05 between 1961 and 1970, then remained at around 0.05 (of natural) until 1980, then essentially failed completely (Fig. 5). However, this pattern in recruitment decline predicts an age composition in 1982 that is about 5 yrs older than what was observed from the samples collected by Dixon (1986). This discrepancy could be the result of the use of gill nets for sampling fish in the 1982 sample that would select for younger fish, resulting in an observed age composition for 1982 that would appear younger than it actually was. Both the 1982 and

1995-1999 data suggest that the last strong recruitment event happened in 1962 (1982 – dominant age in sample of 20 yrs = 1962), while the predictions imply strong recruitment from 1958-62. Other recruitment scenarios, e.g. recruitment declines starting in early or later years, lead to predicted modal ages quite different from those observed. There are not enough age composition samples to warrant fitting more complex time dependent recruitment patterns to the data.

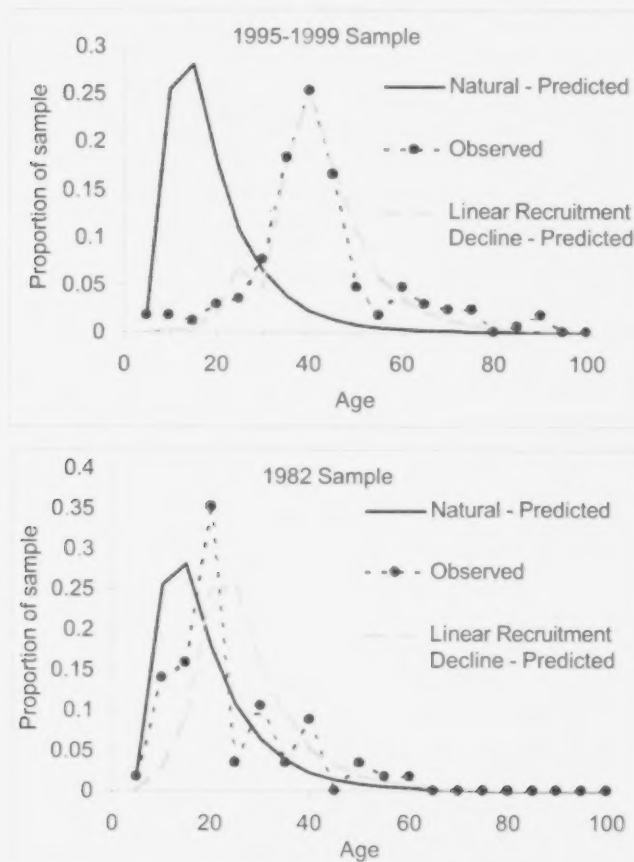


Figure 5. Comparison of age composition from the best-fit balanced population for the Fraser River aggregate stock with observed and predicted age compositions for the Nechako stock for the 1995-1999 (top) and 1982 (bottom) sample periods. The predicted Nechako age composition was generated under the hypothesis that relative reproductive success for the Nechako stock declined linearly from 1.0 to 0.05 between 1961 and 1970, then remained at around 0.05 (of natural) until 1980, then essentially failed completely.

Flows during the presumed spawning period for Nechako sturgeon, as indexed by the mean June flow at Vanderhoof, decreased over the 1964-70 period as the Kemano power production system was brought on line (Fig. 6), and there was also a very low flow period during the mid 1950s as the reservoir was filling. We tried fitting the age composition data by simulating the hypothesis that relative reproductive success H_i is dependent on spawning time flow according to a positive, logistic relationship of the form

$$H_i = F_i^\alpha / (F_h^\alpha + F_i^\alpha) \quad (6)$$

where F_i = mean June flow at Vanderhoof (m^3/sec), F_h = mean flow needed for 50% normal recruitment success, and α is a steepness parameter (larger value implies steeper recruitment response to changes in F_i). At the best fitting parameter estimates ($F_h = 251 \text{ m}^3/\text{sec}$, $\alpha = 7.6$, resulting in the recruitment anomaly red line of Fig. 6, top graph), we obtain simulated age compositions very similar to those observed in 1982 but shifted by - 5 yrs for the 1995-999 prediction (Fig. 7). The flow relationship in (6) incorrectly predicts that there should have been good recruitment (Fig. 6a, red line) following high flows in 1976 (the peak for 25 yr. old fish in the 95-99 age composition), and a peak in the age structure at 35 rather than 40 yrs. This hypothesis also predicts that the decline should have begun with low flows in the early 1950s. Interestingly, the flow relationship does appear to give a bit better fit to the 1982 age data, predicting a relative shortage of older fish at that time due to impacts of low flows in the early 1950s.

In summary, the hypothesis of a direct and immediate relationship between flow and recruitment is a reasonable explanation for apparent recruitment patterns in the 1950's and after 1966, but it is strongly contradicted by the 1976 observation where no noticeable recruitment was produced even though flows were high in that year. We can only explain the 1976 observation using a recruitment-flow relationship if we assume that positive impacts of high flow require consecutive years to have an effect. This would not be surprising in view of the spawning interval for sturgeon; the fish may require more than one year of favourable conditions before committing themselves for spawning.

Population predictions for 'linear decline' (1962-1975) and flow-driven recruitment failure hypotheses are shown in Figure 8. In these scenarios, we assumed a full recovery in juvenile recruitment rates beginning in 2001 to highlight the extensive lag between recruitment recovery and increases in the reproductive component of the population. Both hypotheses result in similar declining trends except that the flow-driven results generate a small increase in the vulnerable population in the mid 1970's from increased flows following the filling period. Note the 25 yr lag between the vulnerable population and the number of mature females resulting from an assumed age of maturity of 27 years (based on a minimum size at maturity of 130 cm). Given this lag, effects from an immediate and completely effective recovery in recruitment rates would not be seen in the spawning population until after 2025. If the current estimate of the vulnerable population size of 500 fish (RL&L 2000) is correct, both hypotheses predict that there will only be about 25 mature females remaining by this time.

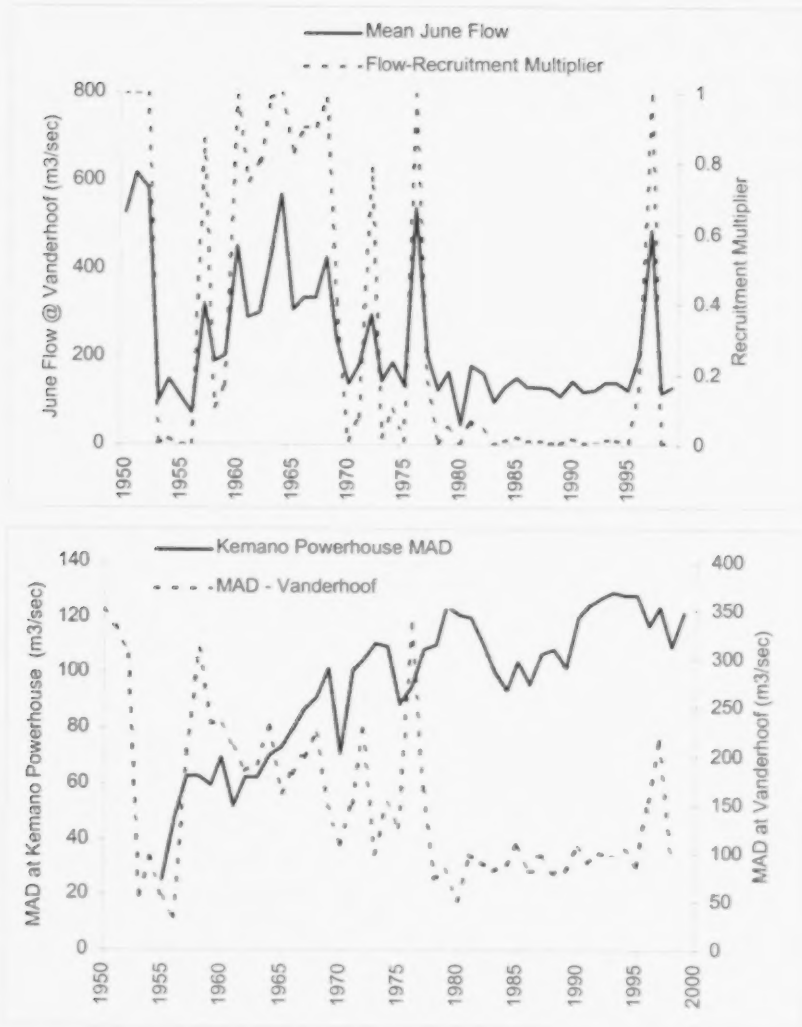


Figure 6. Mean June flow at Vanderhoof on the Nechako River and the relative recruitment rate multiplier generated from these discharges using the best-fit logistic model in Eq. 6 (top), and mean annual discharge (MAD) at Vanderhoof and the Kemano powerhouse (bottom).

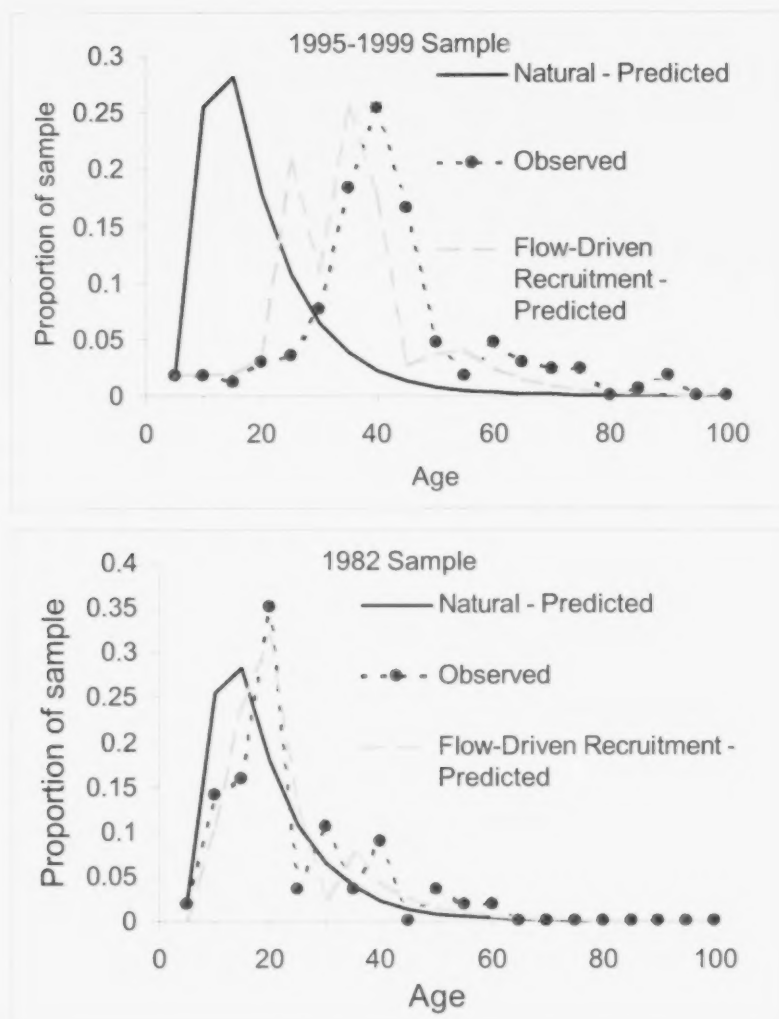


Figure 7. Comparison of age composition from the best-fit balanced population for the Fraser River aggregate stock with observed and predicted age compositions for the Nechako stock for the 1995-1999 (top) and 1982 (bottom) sample periods. The predicted Nechako age composition was generated by predicting relative juvenile recruitment rates from a logistic function driven by average June flow in the Nechako River at Vanderhoof.

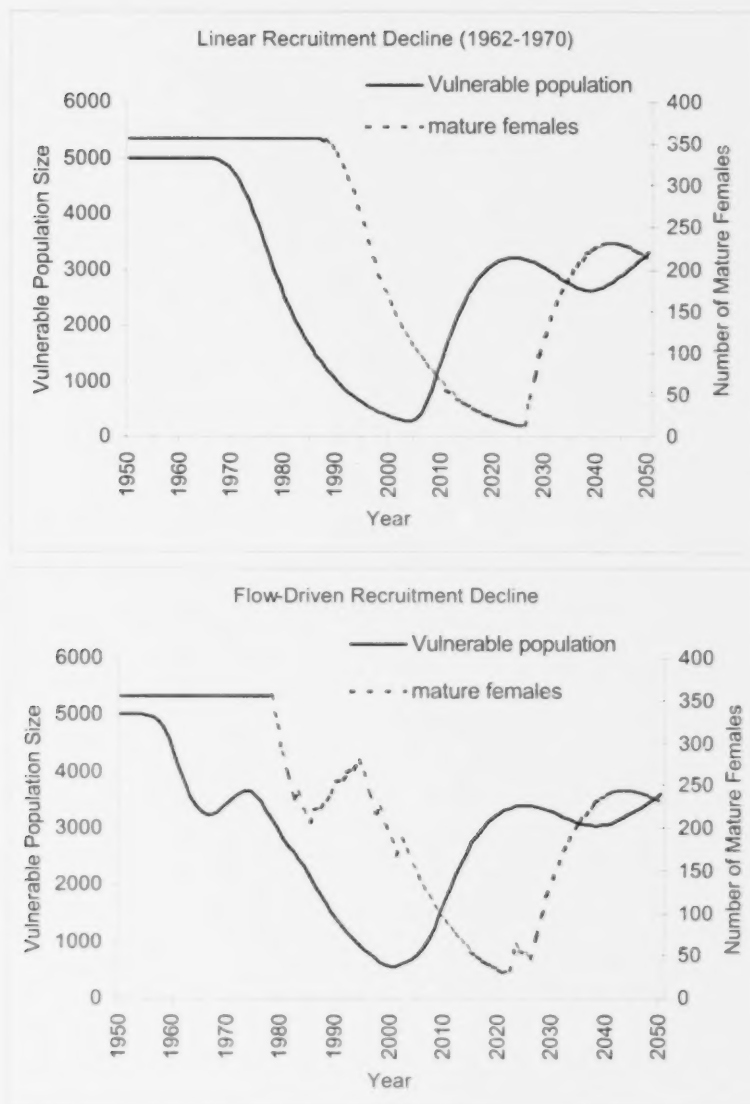


Figure 8. Reconstruction and prediction of vulnerable and mature female population sizes. The future simulation is shown purely to demonstrate how long recovery would take should some effective measure be found for restoring successful reproduction. The top graph is based on the hypotheses that (1) reproductive success declined by 95% over the 1960s and failed almost completely after 1980; and (2) that reproductive success will be recovered to 100% of normal after 2001. The bottom graph is based on the hypothesis that the relative recruitment rate is a logistic function of average June flow in the Nechako River at Vanderhoof.

3.3 Reconstruction of Historical Recruitment Trends from 1990s Age Composition Data

The age composition data for 1995-1999 presumably represent the effects of three main factors: (1) age-dependence in catchability; (2) time dependence in past recruitments; and (3) cumulative loss of fish to natural mortality. Combining these factors, we would expect the number of age 'a' fish sampled in year t, n_{at} , to vary as

$$n_{at} = q_a R_{t-a} e^{-Ma} \quad (7)$$

where q_a is the proportion of age a fish captured by assessment sampling over the period, R_{t-a} is the total recruitment that occurred from spawning in year t-a, and e^{-Ma} is total survival rate of the year t-a recruits to age 'a'. From this relationship, an estimate of R_{t-a} can be constructed for each year t-a as

$$R_{t-a} = (n_{at} e^{Ma}) / q_a \quad (8)$$

If q_a is independent of age 'a' for older fish, then the values of $R_{t-a} = n_{at} e^{Ma}$ represent a time series of estimates of relative historical recruitment rates. Plots of R_{t-a} for alternative assumptions about M are shown in Fig. 9. The simplest way to think about these relative recruitment estimates is as an expansion of the age composition data to account for fish lost from the years of recruitment to the years of observation as older fish (1995-99).

The recruitment reconstructions in Fig. 9 are not valid for fish younger than 20 yrs (i.e. 1980's and later) due to age vulnerability effects, (see Table 1) or for spawning years much before 1950 (too few 45-50 yr old and older fish in the 1995-1999 sample). For the relatively high $M=0.1$ estimated from the age composition data, note that the recruitment estimates are apparently much too high for spawning years before 1940, suggesting that natural mortality rates of older fish may be much lower than 0.1. Expanding the sampled numbers of very old fish (e.g. spawned before 194) by a high mortality rate results in very high recruitment estimates for these cohorts: we suspect that in fact natural mortality rates decline with age so that correct expansion factors for older fish back to their initial recruitment abundance should not be as large.

The recruitment reconstructions support the hypothesis that there was a period of low recruitment in the early-to-mid 1950s while flows were low during the reservoir filling period (compare recruitment and Vanderhoof June flow in Fig. 6), and that recruitment failed over the period between 1960-1970 when the Kemano power system was brought on line. They also suggest the occurrence of a very weak recruitment pulse from the high flow event in 1976 that was not seen in the age composition data from 1982 or 1995-1999. Note that the trends from the recruitment reconstruction are not sensitive to the assumed mortality rate used to back-out the recruitment from the age composition data. The absolute recruitment values are lower as the mortality rate is reduced, but the trends are the same.

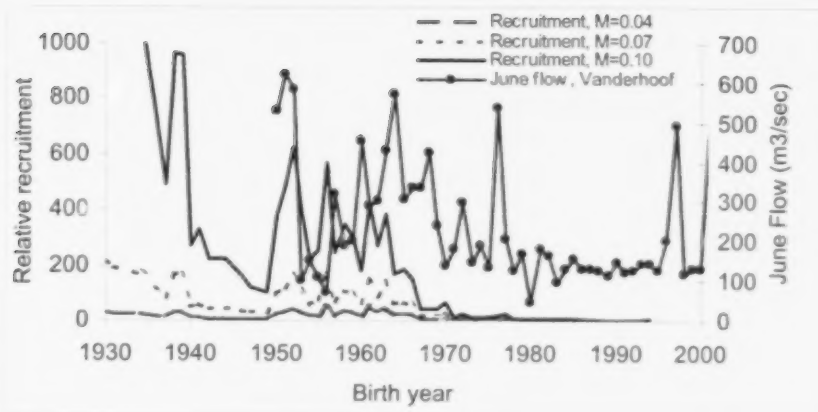


Figure 9. Relative recruitment rates $R_{t,a}$ for Nechako sturgeon, estimated from 1995-99 age composition data based on different assumptions of natural mortality rate (M), compared to average June flows in the Nechako River at Vanderhoof.

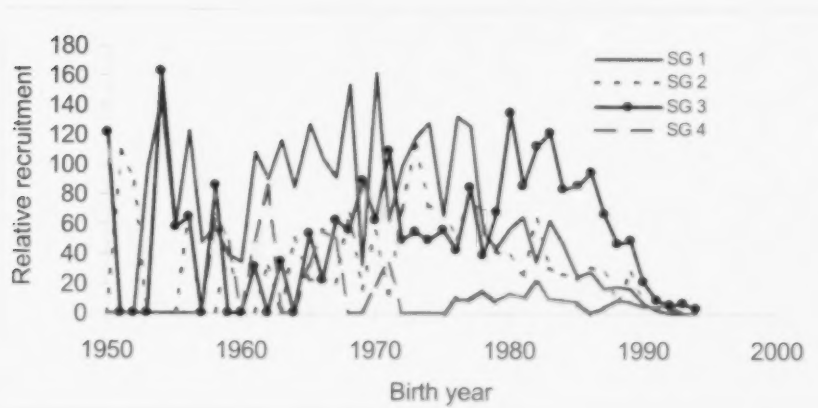


Figure 10. Apparent changes in relative recruitment rates for lower Fraser River stocks, using the same reconstruction method as for the Nechako stock and 1995-99 age composition data. Reconstructions shown only for $M=0.1$ assumption.

For comparison, Fig. 10 shows results of applying the same reconstruction method to 1995-99 age data for other Fraser River stocks (SG1-4), using only the "best" M estimate (0.1). For these stocks, using lower assumed M results in estimated positive trends in recruitment over the last few decades. Note in Fig. 10 that recruitments appear to fail beginning after 1980; this is most likely an effect of reduced vulnerability for younger fish (q_a not constant for younger ages) rather than real recruitment changes. Alternatively, recruitment difficulties could have been exaggerated beginning in the 1980's by augmented summer flows aimed at reducing water temperatures for migrating sockeye salmon. We also cannot reject the possibility that the apparent recruitment failure in the Nechako was caused by young fish moving irreversibly into the Stuart system making the recruitment appear to fail. This hypothesis implies that fish still recruit in the Nechako River and then to move to the Stuart system.

Figure 11 compares the 1950 and later reconstructed recruitments for the Nechako stock to the best fit that we were able to obtain for the flow-recruitment function (eq. 8) by including this function in the population model then predicting the 1995-99 sample age composition. The decline in relative recruitment rates beginning in the mid 1960's is very apparent. The function is obviously not able to explain some features of the data, such as delay in apparent recruitment failure until several years after flows began to fall in the 1960s and failure of high flows in 1976 to result in good relative recruitment. The pattern of prediction failure here hints that there may be a multiple year or delayed effect of flows on reproductive success.

We emphasize that the long intervals between spawning for sturgeon suggest the possibility that fish need to encounter more than one year of favourable conditions before electing to make the relatively costly investment of spawning. Another explanation of delayed response to increased flows is the worrisome possibility that periods of low flow result in a shift in community structure of the river to fish that prey heavily on the eggs and larvae of sturgeon. Such a change in community structure might not be reversed by simple attempts to provide flows over a brief period during the time of spawning.

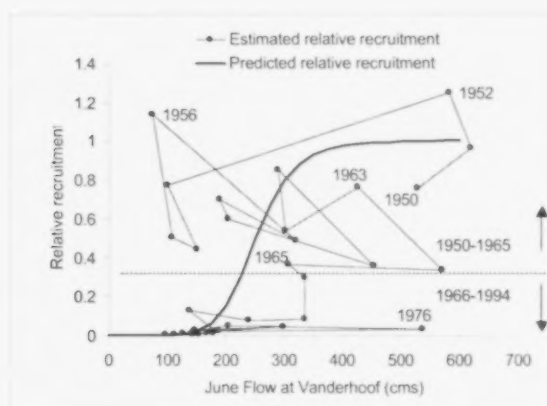


Figure 11. Comparison of reconstructed 1950ff recruitments for the Nechako stock (red data points connected by lines) to the predicted relative recruitments (black line) based on the best-fit logistic function of average June flow in the Nechako River at Vanderhoof.

4.0 Potential Causes of Recruitment Failure

There was considerable discussion at the October workshop on the various factors and mechanisms that potentially led to the recruitment failure of juvenile sturgeon in the Nechako River. Each factor/mechanism was discussed as a hypothesis that was evaluated by comparing the timing of changes in the factor relative to the estimated timing of recruitment failure estimated by the back-calculation of recruitment rates from the age composition data (Section 3.3). In particular, two critical aspects of the recruitment history were used to evaluate the plausibility of each hypothesis: 1) a linear decline in recruitment beginning in the late 1960's; and 2) the failure of the high flow event in 1976 to result in a measurable recruitment response. Management actions, research requirements, and rehabilitation costs associated with each recruitment impact hypothesis were discussed. A description of the hypotheses is presented below and a summary of results is presented in Table 2.

Altered Thermal Regime: Diversion of flows has altered the thermal regime in the Nechako River. This effect could reduce or eliminate spawning events and change bioenergetic requirements of young sturgeon leading to decreased survival rates.

Changes in Hydrograph: Diversion of flows and operations have significantly altered the hydrograph in the Nechako River. Discharge no longer follows a natural seasonal pattern and the spring freshet has become increasingly attenuated with increased diversions. Seasonality in the hydrograph, especially high spring flows followed by a declining hydrograph were hypothesized as a requirement for stimulating a spawning event. Restoring this component of the hydrograph was the preferred experimental regime for some workshop participants although it was recognized that recreating this pattern for a single year might not be sufficient to stimulate a spawning response. Other aspects of changes to the hydrograph in the Nechako River were also discussed including the effects of reducing the mean annual discharge (MAD). However, when the MAD at Vanderhoof is used in the simulations, the 1976 discrepancy is still apparent (Fig. 6 bottom graph). Elevated flows during the summer months resulting from the summer management temperature program were hypothesized to potentially interfere with cues used by young sturgeon that may be critical to their survival. The plausibility of this hypothesis was considered relatively low because prolonged high summer flows were initiated in the early 1980's, well after the recruitment decline had begun.

Spawning Cycle Periodicity: If sturgeon spawning events are tied to cyclical patterns in the returns of sockeye salmon to the Nechako and Stuart systems, spawning may not occur in every year. This hypothesis does not explain the historical decline in sturgeon recruitment, but could be responsible for the lack of a response to the 1976 high flow event. However, as there is no hint of periodicity in the age composition data, spawning events are probably not tied to salmon abundance cycles.

Loss of Spawning Habitat: If traditional spawning areas for sturgeon were located adjacent to the canyon section of the Nechako River (i.e. near Cheslatta Falls), flow reductions would have eliminated this habitat. The loss of such habitat would have resulted in an immediate decline in recruitment that does not match the steady linear decline based on back-calculated recruitment rates.

Predation: There has likely been a strong increase in the number of Cyprinids in the Nechako River in response to changes in habitat and temperature regimes. These fish potentially prey upon juvenile sturgeon. This hypothesis was given a 'High' plausibility rating because the lag time associated with a predator build-up matches the steady recruitment decline, although it does not explain some of the early recruitment failures when the reservoir was filling. Predation risk would increase with other factors affected by flow, such as increased fine sediment on the bed and reduced turbidity.

Stuart River Spawning Miscue: If sturgeon that reared in the Nechako River spawned in the Stuart River, changes in the Nechako River flow regime may have affected the cues that spawning sturgeon used to ascend the Stuart.

Recruitment Requires Sequential Years of Adequate Habitat Conditions: As Nechako discharge controls many of the potential hypotheses for the recruitment failure, it is surprising that the spill of 1976 didn't result in a significant recruitment event. It is hypothesized that consecutive years of high flow may be required to generate a recruitment event. A period of high flow may be required to initiate physiological changes during the winter prior to spawning, and a second event may be required to stimulate spawning and enhance juvenile survival.

Physical Regime Affecting Turbidity and Sedimentation Rates: Flow diversion and impoundment have reduced turbidity in the Nechako River that could in turn reduce the frequency of spawning events and lower juvenile survival rates. However, spill events during the summer months have resulted in large increases in turbidity with no measurable impact on recruitment. Changes in flow regime alone may not result in a sustainable increase in turbidity without additional rehabilitation measures that increase sediment delivery to the Nechako River.

Macrophyte Development: Reductions in peak flows and land use changes have resulted in significant macrophyte development in the Nechako River. Decay of this material would increase biological oxygen demand and reduce dissolved oxygen near the river bed to levels that could impact juvenile sturgeon survival.

Changes in Benthic Habitat: Reductions in peak flows have increased the percentage of sand and finer material on the bed, potentially resulting in reduced juvenile survival rates. Side channel habitat has also been reduced by land use changes and coupled with the reduced springtime freshet, it was hypothesized that rearing in floodplain habitat by juvenile sturgeon has declined over time.

Fishing Mortality: Excessive harvest rates could have reduced the spawning stock to the point that juvenile recruitment became spawner-limited. This hypothesis was considered unlikely as harvest would reduce the abundance of all fish vulnerable to the fishery and not explain the skewed age composition seen in the data.

Land Development: Increased land use along the Nechako River was hypothesized to cause changes in runoff patterns, thermal regimes, and tributary health, possibly affecting the abundance of fish that are eaten by sturgeon.

Table 2. Summary of preliminary hypotheses for recruitment failure of juvenile white sturgeon in the Nechako River. The columns labeled 'Spawn' and 'Juvenile Survival' specify which life history component would be effected by the hypothesis. Plausibility of each hypothesis was evaluated based on the timing of change in the proposed factor relative to the estimated timing of recruitment change from the back-calculated recruitment rates (Section 3.3). The 'Reversibility' column specifies whether the negative impact of the factor can be reversed through a management action.

Hypothesis	Spawn	Juvenile Survival	Plausibility	Reversibility	Cost of Rehabilitation	Research Requirements / Management Action
Thermal Regime	X	X	Medium	Yes	High/Low	Reconstruct natural thermal regime using water release facility on Kenney Dam or by modifying summer temperature management program
Hydrograph						
Loss of spring freshet and natural seasonal pattern	X	X	Medium	Unknown	High	Experimental flow regime
Increased summer discharge		X	Low	Yes	Low unless negative impacts on salmon	Relate natural hydrograph index over years to patterns of growth based on ichthyochronological studies
Spawning Cycle Synchronicity	X		Low	N/A	N/A	Ichthyochronology to determine if spawning cycles were cyclical and correlated with salmon run strength
Loss of Spawning Habitat	X		Low	Yes	High	Experimental flow regime
Predation		X	High	Low (control of predators likely not effective)	Low	Evaluate historical changes in Cyprinid abundance based on work completed by DFO (M.J. Bradford, unpublished data) and rotary screw/IPT data, and NFCP data

Table 2. Con't.

Hypothesis	Spawn	Juvenile Survival	Plausibility	Reversibility	Cost of Rehabilitation	Research Requirements / Management Action
Stuart River Spawning Miscue	X		Low	N/A	N/A	More extensive sampling for spawning activity and juveniles in Stuart River. Synthesis of existing data from this area.
Recruitment Requires Sequential Years of Adequate Habitat Conditions	X	X	High	Yes	High	Experimental flow regimes must span high spring flows for multiple yrs and include a low flow regime in winter to simulate other aspects of natural seasonal pattern in hydrograph
Physical Regime Affecting Turbidity and Sedimentation Rates		X	Medium	Yes	High	Could increase turbidity by excavation/pipeline, potential negative impacts on salmon egg-fry survival. Evaluate DFO turbidity records. Core of Murray Lake to get turbidity history.
Macrophyte Development		X	Medium	Yes	High	Control by harvesting macrophytes and reducing non-compliance of effluent discharge at Vanderhoof. D.O. sampling to test for anoxic conditions near macrophyte beds.
Change in Benthic Habitat		X	Medium	Yes	High	Flushing flow required to reduce fine substrate on bed. Examine aerial photographs.
Fishing Mortality	X		Low	N/A	N/A	Fishing closure already in effect
Land Development		X	Low	Yes	High	Evaluate extent of floodplain habitat and change in species composition in tributaries

5.0 Preliminary Assessment of Options for Experimental Management and Monitoring

The majority of the hypotheses for the causes of recruitment failure in the Nechako sturgeon population that were evaluated at the October workshop were effected by discharge in the Nechako River. The age composition and relative abundance data do not leave much room for uncertainty about the occurrence of a recruitment decline in the Nechako sturgeon stock. But it remains doubtful whether and how this decline was caused by a change in water flows, and hence, whether a reversal of flow conditions would be effective as a mitigation tool. Given the considerable uncertainty as to which hypothesis, or combination of hypotheses caused the recruitment failure, and the reversibility of these causes, discussions during the latter part of the workshop focused on defining an experimental flow regime. The design of the experiment would essentially be a before-after comparison, where current data collected during the 1995-1999 period would be compared with data collected during and after the experimental flow regime. The majority of participants supported an experimental flow regime that reshaped the hydrograph to a more natural regime with stronger seasonality. This would mean increasing discharges during the spring and reducing flows during the summer and fall. The magnitude of the hydrograph was not explicitly discussed, but some participants felt that reshaping the existing water release budget (36.8 cms + SMTP cooling flows of approximately 16 cms) would be a logical first step. Given the failure of the 1976 spill to generate recruitment, most participants at the workshop supported the notion that the experimental hydrograph would have to be repeated over a number of years in the event that consecutive years of higher flows are required to generate a successful recruitment event.

It was recognized that any change in flow regimes would have to be supported by the appropriate organizations (e.g. NEEF, NFCP, NWC, communities residing along the Nechako River) and that hydrograph reshaping would likely involve a reduction in the magnitude of cooling flows targeted towards migrating salmon. The trade-off between higher pre-spawning salmon mortality and the recruitment benefits to the rapidly declining sturgeon population potentially resulting from the experimental flow regime will have to be carefully evaluated by the Nechako Sturgeon Recovery Group and other parties.

Model-based estimates of population trajectories (Fig. 8) highlight the urgent need for stock recovery. The estimated number of mature females in the current population was about 150 fish, thus there is still sufficient spawning stock to generate a recruitment event if suitable habitat conditions are provided. However, there will be a considerable lag before a successful recruitment event can be detected. The model estimates that fish 7-8 yrs old are only 50% vulnerable to sampling gears (Table 1). Thus, there will be at least a 5 year lag between successful spawning and early survival and the time when we can measure the event. Monitoring of egg deposition will provide an immediate response, but will not necessarily be indicative of successful recruitment given experience on the Canadian portion of the Columbia River. Even if recruitment rates are immediately and completely restored to our estimates of natural levels, the spawning population will continue to decline for another 25 yrs until the new recruits reach

maturity. By this time (ca. 2025) the model predicts that there will be less than 25 mature females, and the majority of these fish will be over 80 years old.

In an ideal setting, one would evaluate each experimental treatment in sequence. As each treatment would consist of multiple years of an altered flow or temperature regime, most participants at the workshop agreed that there is little time for this approach in the case of the Nechako sturgeon population. If model projections of population decline are in the right ball park (they are based on the annual mortality rate, which is well defined – Table 1), even a decade of unsuccessful treatment regimes will leave little remaining spawning stock by 2035. Thus, there was support for a 'shotgun' approach to saving the Nechako Sturgeon population that basically involves attempting a number of different restoration strategies at the same time. If successful recruitment is detected, various restoration activities can be removed in a sequential fashion over time to ultimately determine which activity, or combination of activities, caused the successful recruitment.

There was some discussion on the potential use of "conservation aquaculture" techniques as a tool in the Nechako River sturgeon recovery planning process. BC Fisheries makes a significant distinction between **conservation** aquaculture and conventional **production** aquaculture. In conservation aquaculture, maintaining the genetic integrity and diversity of the population is paramount. Such a program would have to be based on a strict breeding plan that would require individual sturgeon families to be raised under segregated conditions such that the contribution of each family to the total population could be controlled at the time of release. This would be done to ensure that one family is not favoured over another and to control the total numbers released to ensure that the wild fish are not genetically swamped. However, it was noted that such a facility would be seen as a stop-gap measure to ensure that there were fish available for experimental purposes and to maintain a base level of recruitment while the factors affecting natural recruitment are addressed under the recovery plan. The overall objective of recovery would still be the rehabilitation of a stable, self-sustaining population of sturgeon in the Nechako River.

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